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Abstract. Typical spacecraft-tracking data support simultaneous refinement of ground-station coordinates and the parameters that influence spacecraft positions. The geodetic parameters reported by Gaposchkin and Lambeck for the 1969 Smithsonian Standard Earth (II) are products of this procedure. As the results from the refinement process become more detailed, especially as a consequence of improved observation techniques, dynamical phenomena within the earth become accessible to study. Both Newton and Kozai have studied the tidal mass displacements in the earth through the effects of this displacement on the orbits of satellites. Subsequently, Kozai isolated a seasonal variation in J_2. Anderle and Beuglass have shown that it is possible to detect changes in position of the earth's pole from analysis of satellite orbits. Still further instrumentation advances, such as laser ranging to decimeter accuracy, very long-baseline radio interferometry, satellite-to-ocean altimeters, satellite surface-force compensation, and satellite-to-satellite tracking, allow investigation of other topics in solid-earth and ocean physics.

1. INITIAL CONSIDERATIONS FOR APPLICATIONS OF SPACE TECHNIQUES TO EARTH PHYSICS

Some of the earliest scientifically useful data from space activities were tracking observations. Their subsequent analysis has revealed many details of the geometry and mass distribution of the earth. Improved spacecraft and ground instrumentation continues to support such analyses, which now include features in the physics of the solid earth and the oceans.

The information about the earth derived to date from tracking data is only a beginning toward the understanding of earth processes that seems possible with observation techniques and accuracies now achievable. In August 1969, some 65 specialists assembled in Williamstown, Massachusetts,* to examine the current status and future promise of the application of space and astronomic techniques to solid-earth and ocean physics [1]. They reported an impressive array of prospects in instrumentation and for new investigations of the earth. The following discussion draws liberally from their conclusions.

As a background for this review, Fig. 1 illustrates very schematically how progress unfolds in the topics of interest here. The process is cyclic; hence, instrumentation is as satisfactory as any other place to begin the discussion. The instruments of initial concern typically measure some quantity that is a function of the position and motion at some time of both a spacecraft and an instrument on earth. Hence, these data carry information about the motion of each end of the station-to-spacecraft vector. This dual character deserves emphasis in a discussion of solid-earth and ocean physics. It is just as valid to consider that the earth is being tracked relative to the spacecraft as it is to consider that the spacecraft is being tracked from ground stations.

The positions of spacecraft and tracking stations each carry different information about the earth. For example, the spacecraft motions depend upon the mass distribution of the earth, including any time dependence. The collective and relative station motions are influenced by many dynamical phenomena of the earth, ranging from the daily rotation to continental drift.

To describe the state and dynamics of the earth and other natural or artificial bodies, at any instance there are current concepts and theories. These theories yield mathematical models or algorithms that can generate

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expected positions and motions for the spacecraft and stations as a function of time. The calculated positions or observable functions of them depend on the values of parameters that enter the models or algorithms.

The conventional data treatment proceeds with an adjustment of these parameter values to minimize the differences between observed and calculated positional quantities. By this general procedure, the parameters involved in motions of the earth and the spacecraft are refined together. As the refinement progresses, the calculated positions of the spacecraft and the ground stations must maintain commensurate accuracies.

In an ideal situation, the models would be refined until they generate values of observable quantities that agree with observed values to within the uncertainties of the observations. Sooner or later, requirements emerge for improved theories, models, and instruments, and so the cycle continues.

Historically, the observation techniques available in 1957 had accuracies far surpassing those of the best earth models and celestial-mechanics algorithms. During the following decade, the theoretical models progressed through many stages of refinement. Until the models began to approach the observations in accuracy, there was little impetus to sharpen observation techniques. Late in the 1960s, when theory about caught up with observation, new instrumentation emerged with vastly improved accuracy. The resulting opportunity for further refined theory now leads to many topics in solid-earth and ocean physics.

2. STATUS OF EARTH GEOMETRY AND KINEMATICS

A necessary first step toward analysis of tracking data is selection of a coordinate system or systems in which to express the mathematical formalism [2]. Whatever system is chosen for convenience, it should be related in some well-defined way to an inertial coordinate system or to a sufficiently accurate approximation of an inertial system. A fundamental time system is also necessary; one based on atomic clocks is the best choice.

Distant astronomical objects that appear as stationary point sources provide a usable means to define directions for coordinate axes in an inertial system. This choice leads in § 4 to a consideration of the techniques by which other directions can be measured with respect to directions to the distant sources.

The simplest model for the position of a point on the surface of the earth assumes first that a coordinate system can be defined that is fixed in the solid earth. (This assumption will have to reconsidered in § 6.) The coordinates of a reference point on a tracking instrument can then be expressed in this terrestrial system.

In this simplest model, the time-dependent orientation of the terrestrial system is specified relative to astronomical right ascension and declination. The direction of the rotational axis of the earth and the angular position about this axis are measured and tabulated by international services (Bureau International de l'Heure, BIH; and International Polar Motion Service, IPMS) using reference stars and classical astronomical methods.

When the early satellites were launched, the orientation as a function of time for terrestrial coordinate axes was available from the astronomical services with far better accuracy than the coordinates of a tracking instrument could be found globally in the terrestrial system by conventional surveying procedures. Thus, one early requirement from satellite tracking was a refinement of instrument coordinates.

To refine instrument coordinates, two principal methods have been widely used. One, geometric in character, depends on simultaneous satellite observations from two or more sites. A second depends on many individual observations of one or more satellites whose orbits are accurately represented by some orbit-determination procedure. By using a combination of both methods, E. M. Gaposchkin and K. Lambeck in 1969 obtained coordinates with an uncertainty of between 5 and 10 m for the principal camera and laser satellite-tracking sites [3,4]. Other investigators have produced station coordinates of similar accuracy by using TRANET doppler tracking data [5] and BC-4 camera observations of balloon satellites [6].

The uncertainties in the pole position and the rotational position of the earth as tabulated by the international services are roughly comparable to these uncertainties in station position. To improve the position model for ground stations by, say, an order of magnitude, terrestrial station coordinates, polar position, and earth-rotation angles all need to be improved.

R. J. Anderle and L. K. Beuglass in 1969 first used doppler satellite-tracking data for U.S. Navy navigation satellites to determine the pole position independently of the conventional astronomical determinations [7]. In this approach, the orbits of one or more satellites essentially define the reference to which the pole position is measured.

This calculation was extended in 1970 to cover the years 1967, 1968, and 1969 [8]. For 1969, they report random errors in the computed pole position of 1 m on the basis of 48 h of observations of one satellite. However, a bias of 1 to 2 m exists with respect to values from the BIH or IPMS. Fig. 2, adapted from their paper, illustrates this agreement.

A calculation similar to that of Anderle and Beuglass could probably extract from satellite observations the angular position of the earth about its axis (UT1). At the equator, a point on the earth moves almost 0.5 m $msec^{-1}$. An examination of differences between UT1 tabulations from different time services reveals differences corresponding to a displacement of almost 5 m. Gaposchkin and Lambeck [4] feel that the uncertainty in UT1 limits the accuracy of their station-coordinate determinations.

In summary, the model (illustrated in Fig. 3) now in general use for station positions as a function of atomic time adopts a fixed geocentric coordinate system in the earth with its Z axis through the conventional mean pole of 1900-1905 and its X-Z plane defined by adopted longitudes for the observing sites of the BIH. Station coordinates in this global system are most accurately obtained from satellite observations. The models adopt a rotation direction in space provided by formulas for astronomical precession and nutation, and instantaneous pole position in the earth as tabulated by BIH, IPMS, or the Dahlgren Polar Monitoring Service (DPMS). The angular rotation about this axis is obtained from tables of UT1 provided by the BIH.

It is worth emphasizing that in this model, space techniques already play an essential or important role in locating the center of mass, refining station coordinates, and measuring polar motion.

3. STATUS OF GEOPOTENTIAL MODELS

The mass distribution of the earth has many irregularities that generate a correspondingly irregular gravitational field, which in turn induces many measurable perturbations in the orbits of artificial satellites. If the geopotential is represented as a series of spherical harmonics, the coefficients in this series can be treated as parameters whose values can be determined by differential adjustment, as sketched in § 1.

As more and more tracking data accumulated on a variety of satellites, more terms could be included in the solutions for geopotential coefficients. The solution by Gaposchkin and Lambeck [3, 4] for the 1969 Smithsonian Standard Earth (II) contains 296 coefficients for tesseral harmonics. Twenty zonal-harmonic coefficients derived by Y. Kozai [9] are also part of this geopotential model.

Orbits of 21 satellites contributed to this solution. French and United States laser ranging data with an accuracy of a few meters were available for six of the satellites. Baker-Nunn photographs provided the bulk of the data; they have an accuracy of a few arcsec. The geopotential solution also incorporated surface-gravity measurements. Fig. 4 is a map of the geoid calculated from the 1969 Smithsonian Standard Earth (II).

When this geopotential was used in determining several week-long arcs for Geos 1 and Geos 2, the laser data always had an rms deviation of less than 10 m, with the mean at 7 m. Thus, the station coordinates and satellite positions associated with the 1969 Smithsonian Standard Earth (II) have comparable accuracies.

Efforts to analyze satellite orbits to detect time-dependent terms in the geopotential due to tidal deformations began in 1965 [10]. The tidal-disturbing potential due to the sun and moon can be represented to a first approximation in terms of spherical harmonics of the second degree. This potential and the external potential due to the resulting deformations of the earth are related by a constant k, the ratio of the additional potential produced by deformation to the deforming potential. The value of this Love's number k depends on the elastic and other properties of the earth.

In subsequent analyses, R. R. Newton [11] used four satellites in polar orbits for which doppler tracking data from the TRANET system were available over intervals of 6 to 18 months. He obtained the following Love's numbers:

$k_S = 0.359 \pm 0.042$ for the solar tides,
$k_M = 0.314 \pm 0.036$ for the lunar tides,
$k = 0.336 \pm 0.028$ as a combined value.

In an independent analysis, Kozai [12], using Baker-Nunn data covering intervals from 2 to 5 y for three satellites at lower inclinations, obtained the value

$$k = 0.29 \pm 0.03 \quad .$$

Both Newton and Kozai also derived the phase of the earth tides relative to the longitude of the sun or the moon. Kozai obtained a lag angle of $5° \pm 3°$ for solar tides, and Newton obtained $0\overset{\circ}{.}8 \pm 0\overset{\circ}{.}3$ for solar tides and $2\overset{\circ}{.}1 \pm 0\overset{\circ}{.}2$ for lunar tides. This is an important quantity in theories of tidal dissipation of rotational energy.

Kozai [13] has also identified an annual variation in J_2, the coefficient of the oblateness term in the geopotential. His analysis used Baker-Nunn observations of two satellites, 1960 ι2 and 1962 βμ1, with inclinations of 47° and 50°, respectively. He obtained an annual variation of J_2 as

$$\delta J_2 = \underset{\pm 0.2}{1.3} \times 10^{-9} \cos (2\pi t + \underset{\pm 10°}{160°}) \quad ,$$

where the epoch is at the beginning of the year.

The speed of rotation of the earth also has an annual term. Kozai concludes that about half the seasonal variation in the length of the day is due to the change in the principal moment of inertia calculated from this variation in J_2. The other half is presumably due to wind in the atmosphere.

In summary, the best available model of the geopotential contains some 300 terms in a spherical-harmonic representation. This representation is complete through indices 16, 16, but some coefficients above 12, 12 are weakly determined. Time-dependent tidal terms of second degree and an annual variation of J_2 can be appended to this model.

4. INSTRUMENTATION ADVANCES

The satellite-tracking instruments of 1960 can be characterized grossly, for typical satellites, as systems of 10-m accuracy or equivalent. Sections 2 and 3 conclude that analyses of data from these systems 10 y later support mathematical models providing station and satellite positions to roughly 10-m uncertainty. These analyses also yield significant information about polar motion, earth tides, and annual variations of the geopotential. However, the capability of these early systems to support further advances in earth physics has been nearly exhausted.

Progress in time-interval and epoch measurement was the spearhead for the development of instruments of improved accuracy. The velocity of light implies the elementary but pertinent relationship: 1 m corresponds to 3 nsec flight time, and 10 cm corresponds to 0.3 nsec. For brief intervals, such as the round trip for a light pulse between a station and a satellite, even crystal oscillators can provide these timing precisions. For longer intervals, at least rubidium or cesium oscillators are necessary. For demanding techniques such as long-baseline radio interferometry, the capabilities of hydrogen-maser clocks are called for [14]. Fig. 5, adapted from Levine and Vessot, illustrates the typical stability of these alternative standards as a function of averaging time. The curve for hydrogen-maser clocks is obtained by comparing two such systems.

Ruby-laser ranging instruments introduced on an experimental basis in 1964 were the first tracking systems to demonstrate an accuracy approaching 1 m [15]. The range is calculated from the time required for a light pulse to reach the satellite and return. A useful block of data from five laser systems tracking six satellites with retroreflectors entered the 1969 Smithsonian Standard Earth (II). In 1969, range measurements were initiated to the retroreflector array placed on the moon by Apollo 11 [16, 17]. The International Satellite Geodesy Experiment (ISAGEX), scheduled to begin in the latter part of 1970, anticipates participation by more than 10 laser systems with global distribution [18]. Even these few unrelated remarks about laser tracking indicate that this activity has achieved a substantial level of operational maturity.

However, the full potential of the laser technique has yet to be realized. Both existing transmitters and the satellite retroreflectors now have the ability to provide 0.1-nsec ranging. Currently, receivers are able to achieve an accuracy of only about 1 nsec, so some improvement in photodetectors would be needed to reach 0.1-nsec precision.

It seems, however, that tropospheric-propagation uncertainties will be a basic limitation in laser ranging from the earth's surface. Using surface measurements of refractive index to estimate the necessary corrections, Bean and Thayer [19] show that the ultimate accuracy of single-wavelength optical ranging to satellites or the moon appears to be limited to about 6 cm, or 2.5% of the total correction at the zenith. Radio systems are worse by a factor of about 2 because of the increased influence of water vapor in the radio spectral region.

Of the radio frequency systems with prospects of 1-m or better accuracy, very long-baseline interferometry (commonly abbreviated VLBI) seems to offer the greatest versatility. This technique depends upon local frequency standards of high quality — preferably hydrogen masers — at two or more radio telescopes separated by distances on earth as great as allowed by common visibility of a radio source [20]. The frequency standards provide time references for magnetic tape recordings of signals from the same space source. These tapes are later correlated at a central computing facility, and the time difference for arrival of the same wavefront is determined.

One application of this technique uses natural radio sources of small apparent size. For example, a number of compact, distant radio sources remain unresolved at 6-cm wavelength over a 6319-km baseline between the United States and Sweden [21]. With data from a suitable observation campaign on several such point sources, the baseline distance and direction can be determined. The directions are relative to directions defined by the astronomical sources. With due refinement of the technique, there seems to be no obstacle in principle to achieving 0.001-arcsec accuracy.

Another application of VLBI is to spacecraft tracking. Several groups have demonstrated this possibility for interplanetary spacecraft [22] or for satellites in earth-synchronous orbits [23, 24]. If both natural and artificial sources figure in an observing campaign, the satellite directions can be referenced to directions defined by the natural sources.

Satellite-to-satellite range-rate tracking offers substantial advantages. A very high satellite can track a low satellite continuously for about half the latter's orbit. This continuity should allow application of the same data-analysis techniques used so successfully by Muller and Sjogren [25] to determine the moon's potential from range-rate tracking of lunar orbiters.

Satellite-to-satellite tracking also has the advantage that the tropospheric-propagation errors unavoidable from ground-station tracking are eliminated. A suitable choice of frequencies can circumvent ionosphere-propagation problems. With instrumentation components and concepts already identifiable, it seems possible in a few years to achieve accuracies of 0.03 mm sec^{-1}.

A first experiment with satellite-to-satellite tracking is scheduled between ATS-F, in a synchronous orbit, and Nimbus-E [26].

To sense as many features of the gravity field as possible, ultimately the tracked satellite should be as low as practical. A satellite in a low orbit but free of atmospheric-drag complications is possible with a surface-force compensation system [27, 28]. The essential element of such a system is an unsupported proof mass contained in a cavity at the mass center of the satellite. A control system in the satellite senses motions of the satellite relative to the proof mass and actuates small thrusters that force the satellite to follow the proof mass without touching it. Hence, the satellite follows an orbit influenced only by gravitational forces. Such a system is scheduled for flight, perhaps in 1971, on an experimental navigation satellite.

Satellite-to-ocean radio altimeters have been recognized as a possibility for many years [29-31]. An experimental instrument flew on a Saturn rocket in 1963 [32].

It seems possible with available components to build a space-qualified altimeter in which the error contributed by the altimeter does not exceed 1 m for averaging times of 10 sec. To achieve an accuracy of 10 cm, it will be necessary to develop sophisticated satellite hardware, to find a way to make the propagation corrections, and to cope with the uncertainties in sea-surface scattering. As later sections will indicate, a 1-m instrument will be useful for geopotential refinement and for tidal measurements on the continental shelves. The 10-cm capability is eventually needed for physical oceanography.

Certainly the instruments discussed above will not be the only ones that contribute to future space programs in earth physics. They are probably the instruments that now seem most likely to provide major advances.

5. PROSPECTS FOR SHORT-TERM DYNAMICS OF THE EARTH

The short-term dynamical phenomena now recognized as significant for the earth fall into three broad groupings: rotational motions, tides, and temporal variations of the geopotential. The measurement techniques discussed in the previous section promise data for substantial advances in each of these topics.

A judicious choice of fundamental coordinate systems becomes increasingly important — and difficult — as the treatments of these earth phenomena attain ever greater precision. The reference systems must be defined at least to an accuracy comparable to that required to express and to analyze the phenomena under investigation. Both inertial and terrestrial systems are needed.

A catalog of positions for astronomical objects seems still to be the most promising tool to define an inertial reference system. The minimum requirement should be 0.01-arcsec uncertainty for star positions and proper motions. It is questionable whether ground techniques could provide this accuracy in optical frequencies, mainly because of atmospheric-propagation effects. Perhaps an orbiting astrographic telescope could generate the data for an improved catalog of optical stars. In principle, a more precise inertial system could be established with a catalog of very distant point radio sources generated by VLBI techniques. An accuracy of 0.001 arcsec is expected with this method.

The required terrestrial coordinate system should have its origin at the earth's center of mass and in principle could have its Z axis defined by the principal axis of inertia. Satellite dynamics already provide the best location of the center of mass and can determine the location of the principal axes of inertia. The geopotential terms with coefficients C_{21} and S_{21} are usually taken to be zero because they are rigorously zero for an expansion about the principal axis of inertia. For an expansion about the adopted geographic pole, C_{21} and S_{21} will be very small but not zero. Their values change as the principal axis moves around the earth. With enough refinement of the geopotential representation and tracking accuracy, values for C_{21} and S_{21} can be determined as a function of time.

Because the principal axes may not be determined to the required accuracy for some time, arbitrary geographic axes could be used in the interim. The relative positions of the geographic Z axis, the instantaneous spin axis, the axis of inertia, and the angular-momentum axis would be tabulated as functions of atomic time.

In practice, the terrestrial system would be realized by a model assigning coordinates and their time variations to a number of fundamental observing stations. Some of the stations would have optical or VLBI instruments monitoring the motions of the earth relative to the catalog stars. Some stations would have systems tracking the spacecraft employed to determine the center of mass and principal axes of the earth. The fundamental station-coordinate model would be refined occasionally on the basis of all the observations by using a procedure along the lines of Fig. 1. An accuracy of 1 m is expected to be achieved in the next few years, and of 10 cm later in the 1970s.

The procedures that relate the inertial and the terrestrial coordinate systems as a function of time can equivalently be viewed as the means of monitoring the rotational motion of the earth. The earth, of course, rotates about an instantaneous axis that continuously changes. Its direction in space has a 25 800-y cycle (astronomical precession and nutation), caused mainly by torques from lunar and solar gravitational interactions with the oblateness of the earth.

The instantaneous axis of rotation relative to the arbitrary geographical axes in current use appears to have a secular motion of the order of 0.003 arcsec y^{-1} [33]. The axis also performs an irregular precession or wobble with an amplitude of roughly 0."15 arcsec and with two main periods, of 12 and about 14 months. The 14-month component is the Chandler wobble. There is some indication of longer period terms, but no noticeable feature at frequencies higher than 1 cycle y^{-1} in the spectrum derived from current measurements.

Comparisons of pole paths generated by IPMS and BIH show differences as great as 0.1 arcsec ($\sim$ 3 m). This is presumably some indication of the accuracy of past methods. For 1969, Anderle and Beuglass [8] report differences of about 1 m between their satellite-derived pole position and values published by BIH or IPMS.

Unresolved questions about the Chandler wobble include the excitation and damping mechanisms that control its character. Proposed models of excitation mechanisms resort to changes in mass distribution of the atmosphere, electromagnetic core-mantle coupling, and extensive mass shifts accompanying earthquakes, but all seem to fall short of predicting the observed amplitude. Some observational support for the earthquake-excitation hypothesis has been found in a reported correlation between times of occurrence of major earthquakes and changes in the BIH pole path [34].

More accurate determinations of the pole path should help resolve the theory of the Chandler wobble and other features of polar motion. Using either precise satellite ranging or VLBI techniques, measurement of pole positions to 0.01 arcsec (0.3 m) at 2-day intervals would seem to be a useful and achievable objective.

The rate of rotation of the earth about its instantaneous axis shows secular accelerations ($\sim 2 \times 10^{-10}\ y^{-1}$), irregular accelerations ($\sim 10^{-9}\ y^{-1}$), seasonal fluctuations (0.5 msec in length of day), and irregularities of frequency higher than 1 cycle y^{-1}. Explanations of the secular accelerations involve tidal dissipation or perhaps angular momentum exchange between the mantle and the core. Seasonal fluctuations are thought to be due to winds and tides. Irregular changes are poorly understood and may have their origins in atmospheric interactions with the sea and earth or within the earth.

A reasonable accuracy goal for measurements of the rotation about the instantaneous axis would seem to be 0.01 arcsec on a daily basis. This would not only support a more penetrating search for the origins of changes in the rotation rate but would also provide the necessary station-position accuracy for orbital analyses.

The sun and the moon generate tidal forces that produce low-frequency oscillations in the solid body of the earth, with a maximum surface-elevation excursion of about 50 cm near the equator. Two principal aspects of these earth tides can be investigated by space techniques.

One apparent possibility is the measurement of all three spatial components of the actual motion executed by a ground-based instrument. This motion can be extracted from laser-range and VLBI data when they attain decimeter accuracies.

Another measurement, already demonstrated, concerns the total mass displacement associated with tidal deformation. Section 3 discussed the status of this measurement. As further refinements of the gravity field evolve, particularly from accurate long-term tracking, the tidal mass displacements should exhibit details that will be useful in separating the earth and ocean tides and in identifying the various spectral components of the tides.

A later section discusses the direct measurement of ocean tides by a satellite altimeter. The most important contribution from space techniques to an understanding of solid-earth tides may come indirectly from the ocean measurements. This seems likely because the ocean-tide loading on continental margins is an important factor in the analysis of earth tides, and this effect is currently very difficult to treat because the ocean tides are poorly known.

Section 3 considered the successful detection of seasonally varying geopotential terms, as well as tidally induced time-dependent effects. Surely, nontidal time dependence in the geopotential is a fruitful topic for more detailed examination as satellite tracking and orbital analyses evolve to greater accuracy. There will be many correlations of these effects to be made with polar motion and variations in the rotation of the earth.

6. PROSPECTS FOR LONG-TERM DYNAMICS OF THE EARTH

A compelling accumulation of evidence now indicates that the earth's surface is extremely mobile. Large surface blocks or plates 50 to 100 km thick and thousands of kilometers in horizontal extent seem to be moving relative to each other at average long-term rates from 1 to 15 cm y^{-1} [35, 36]. The interactions of these plates appear to be responsible for a wide variety of effects, including large earthquakes, mountain building, generation of tsunamis, and confinement of nearly all active volcanoes to only a few narrow belts. Almost all large-scale geological and geophysical phenomena occurring in the outer 600 km of the earth appear to be intimately related to this global pattern of motions.

Rudimentary models of crustal motions based on existing geophysical data can evaluate the anticipated relative motion of arbitrary points on the earth's surface [35]. However, continental drift and other large-scale earth deformations have not yet been detected conclusively by direct astronomical or geodetic techniques. The possibility of such measurements by the techniques discussed in § 4 is an exciting prospect to promote further understanding of the long-term dynamics of the earth. Laser ranging to the moon or artificial satellites in stable orbits, and VLBI observations of natural and artificial sources all promise 10-cm accuracy once the instrument refinements already identified have been made. Appropriate global observation campaigns that integrate these several techniques must be planned and executed in due course to realize the desired measurements of crustal motions. Such campaigns should evolve naturally as successors to cooperative international efforts such as ISAGEX.

It is important not only to measure the relative motions of the surface plates but also to find their absolute motions with respect to well-defined fundamental coordinate systems. Clearly, if the plates and sites on them are moving about as they seem to be, a coordinate system anchored to geographical sites is not a well-defined one. Space and astronomical techniques offer some possible approaches to this problem, as discussed in § 5.

The relationships between space capabilities and conventional or innovative surface techniques must also receive due attention in plans for future observation programs. The space techniques make their greatest contribution when applied on a global or at least a continental scale. But there is limited value in knowing that a radio telescope site in Europe has a certain motion relative to a site in North America if it is not known whether the sites are moving locally relative to some mean coordinates for their crustal block. Local surface geophysical measurements must relate fundamental instrument sites to their surroundings. Local measurements across fault zones, island arcs, and in general across the contacts of surface plates are necessary to a comprehensive model for motions of points on the earth's surface.

A complicating aspect to this whole picture is the recognition that the motions, at least locally, are not uniform. Across a feature such as the San Andreas fault, there can be both sudden motions accompanying earthquakes, and gradual deformations as strain accumulates. Whether something analagous is true for the motion of whole crustal blocks is not known, and the answer must be sought eventually in the observation programs.

It is not scientifically sufficient only to measure surface motions; it is also important to ask what can be learned about the mechanisms that drive the motions. Clearly, the plate motions themselves are related to the driving forces, but in a complicated way because they can transmit forces over distances of thousands of miles. Another relevant factor is the gravity field determined by satellite techniques. Kaula[37] has discussed some relationships between geopotential models and the patterns of tectonic activity.

Present published geopotential determinations are limited to spherical harmonics of degree 16, plus assorted higher terms related to orbital resonance. Yet simple calculations show that the gravity field will not be dominated by the strength of the lithosphere until degree 50. It therefore appears that extended representations of the geopotential can supply much more information about the driving mechanisms. Fortunately, both satellite-to-ocean altimetry and satellite-to-satellite tracking can provide data for substantial enlargement of geopotential models.

7. PROSPECTS FOR OCEAN PHYSICS

A satellite-to-ocean altimeter is a natural tool to apply to problems of ocean physics [29, 38]. The information to be derived from the altitude data depends strongly on the accuracy of the measurement. A resolution of ±5 m should provide usefully detailed information concerning the shape of the geoid, but very little oceanographic information. A resolution of ±1 m would permit the detection of tides on continental shelves, storm surges, and possibly the surface elevations associated with some currents. A resolution of ±0.1 m would permit detection of the general ocean circulation, tides, and other dynamical processes affecting sea level.

This progression of objectives corresponds to the difference between an equipotential surface and the ocean profile. At 5-m resolution, the two surfaces are indistinguishable, and a measurement of the profile is essentially a measurement of the geoid. Objectives of physical oceanography require a measurement of the difference between the topography of the sea surface and the geoid, and this difference is typically in the decimeter range.

An altimeter with an uncertainty of a few meters poses no severe design or construction problems [29-31]. Such an instrument is being seriously considered for flight on the next Geos satellite. Besides demonstrating the altimeter concept, the objective will be refinement of the geopotential through measurement of the ocean geoid.

Acquisition of altitudes of decimeter accuracy is a more difficult undertaking, as discussed in § 4. Further, the satellite-orbit calculations must achieve an uncertainty in the decimeter range for the fullest use of the data in mapping the global ocean surface. The best geopotential models from which to derive the geoid for the ocean will probably come from satellite-to-satellite tracking. However, this technique may not be accurate enough to pick up geoid variations of less than 100-km wavelength. Thus, the ultimate objectives of ocean physics pose measurement problems that remain to be fully resolved.

Measurements of tides with useful accuracy for the deep ocean also demand the ultimate in altimeter refinement and sophisticated data processing.

The general circulation pattern of the oceans is a fundamental problem in physical oceanography that can be attacked effectively by space techniques. The solution could be realized from a spacecraft by monitoring the positions of free-drifting tracking beacons. The beacons could be carried either by surface buoys or in subsurface floats that periodically rise to the surface and are there located by the satellite. The daily position should be obtained to an accuracy of 1 km or better.

Another application of space techniques to oceanography concerns the adequate horizontal positioning of research vessels. A useful system should provide the position of a moving ship to ±100 m in a global coordinate system.

8. TECHNOLOGICAL INTEGRATION AND INTERNATIONAL COOPERATION

The global nature of most significant problems in earth physics dictates that their solutions require global distributions of observations. The interaction between the several dynamical subsystems of the earth demands coordination of the observation campaigns mounted for various objectives. Hence, for maximum effectiveness, technological integration and international cooperation are essential to a progressive investigation of topics in earth physics.

The instrumentation panel of the Williamstown study [1] offered one example of how a unified system of ground and spacecraft instruments might be assembled to meet most requirements of a vigorous program in earth physics. With respect to international coordination, there is fortunately a long tradition of productive global cooperation on these topics. The BIH, the IPMS, the Smithsonian tracking network, and the ISAGEX are but a few examples.

All these considerations, and the substantial scientific results to date, support the conclusion that the new decade promises to be a golden age for the application of space and astronomical techniques to earth physics.

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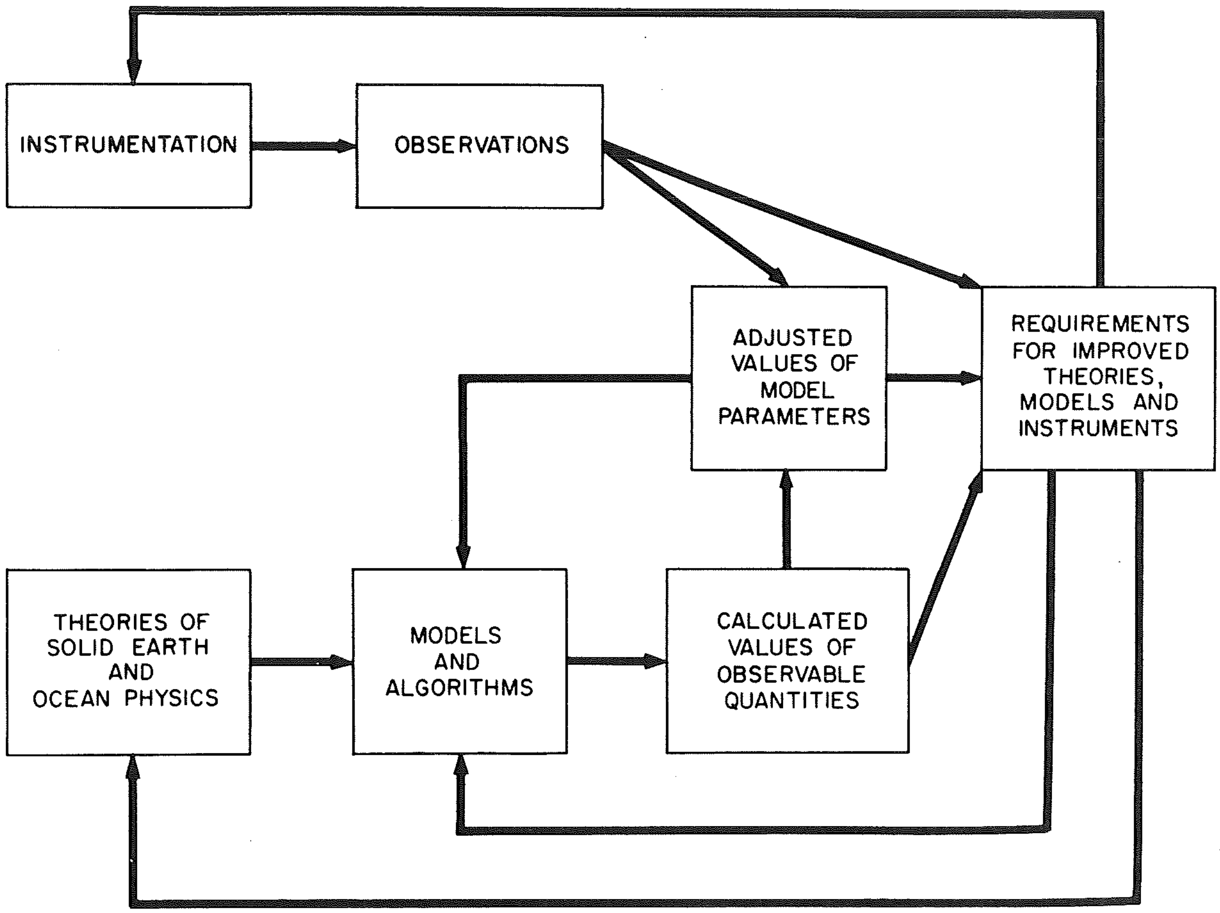

Fig. 1. Schematic information cycle for application of space techniques to solid-earth and ocean physics.

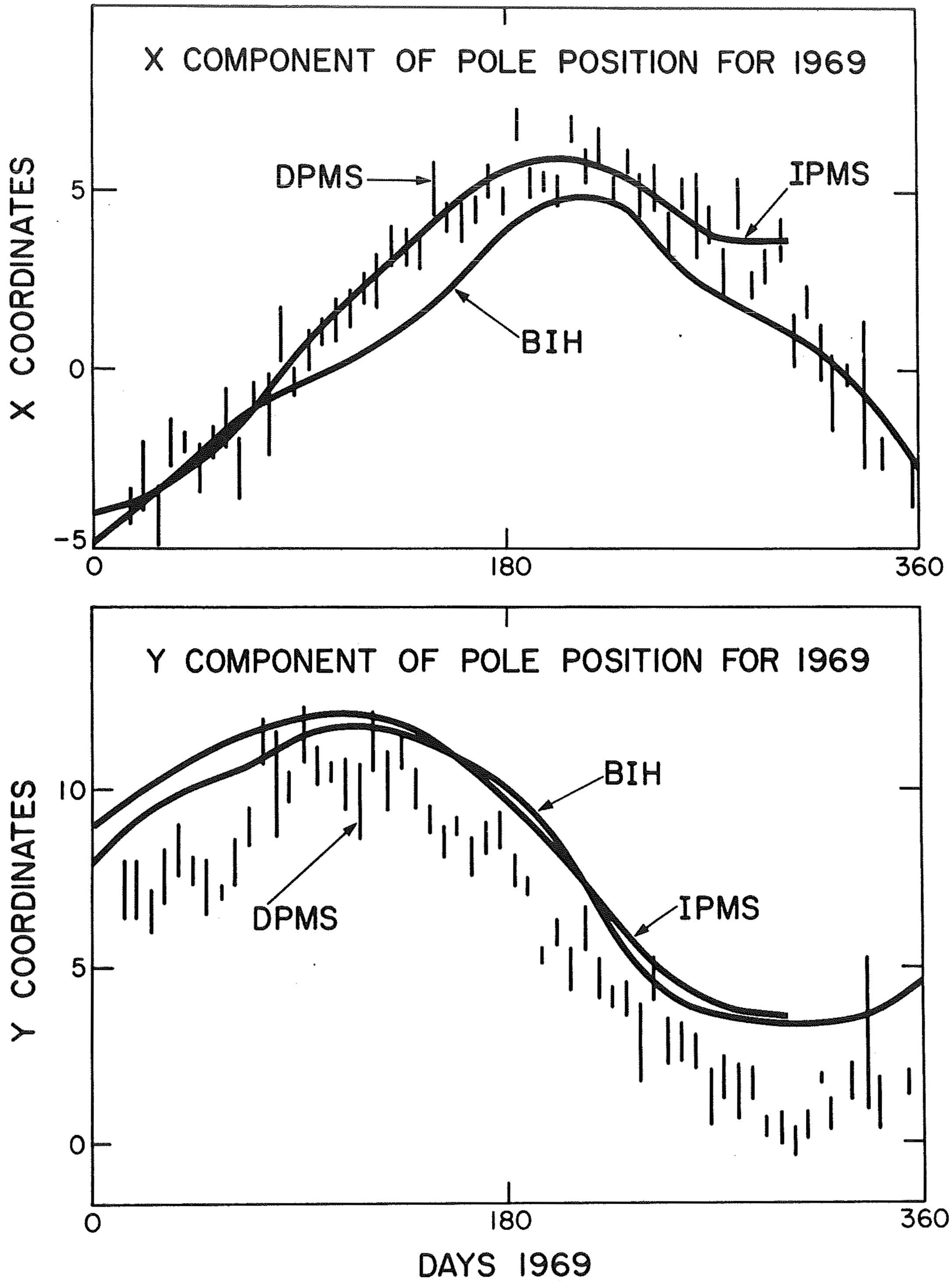

Fig. 2. Components of the pole position for 1969 relative to the mean pole of 1900-1905, from Anderle and Beuglass [8].

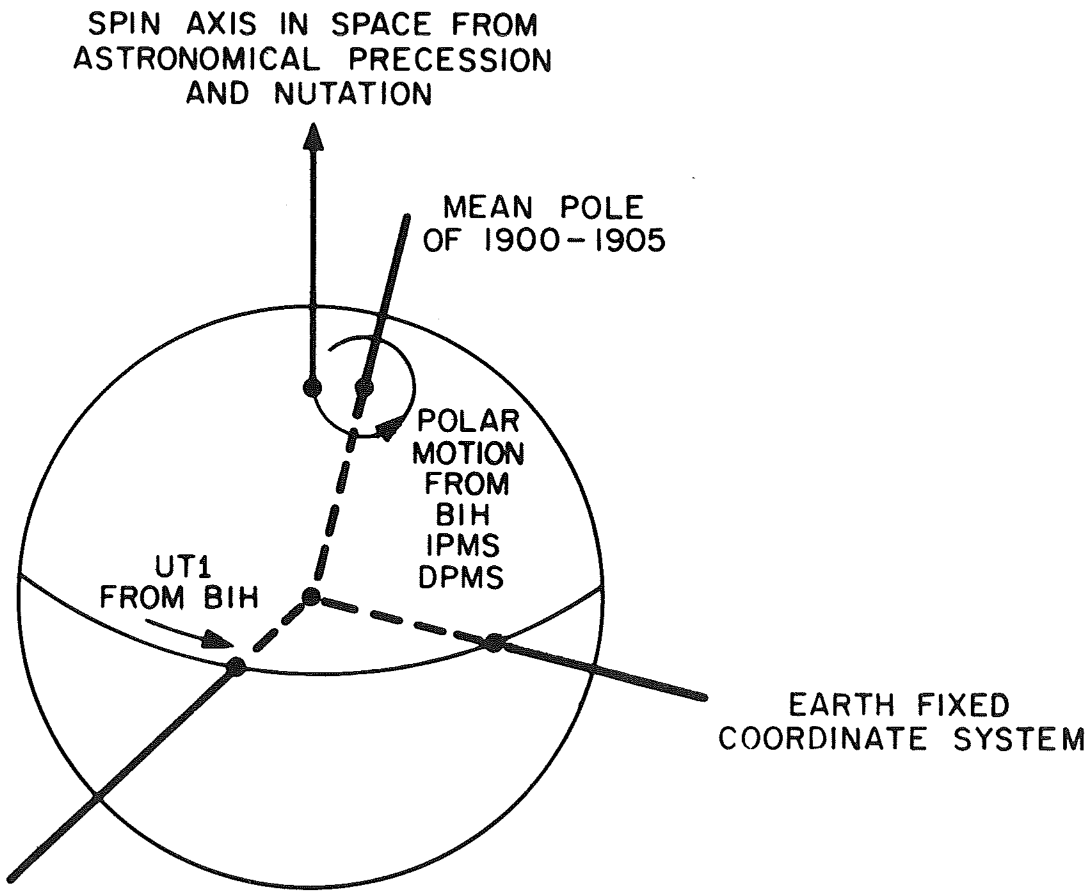

Fig. 3. Current model for calculating the position of a ground station as a function of time.

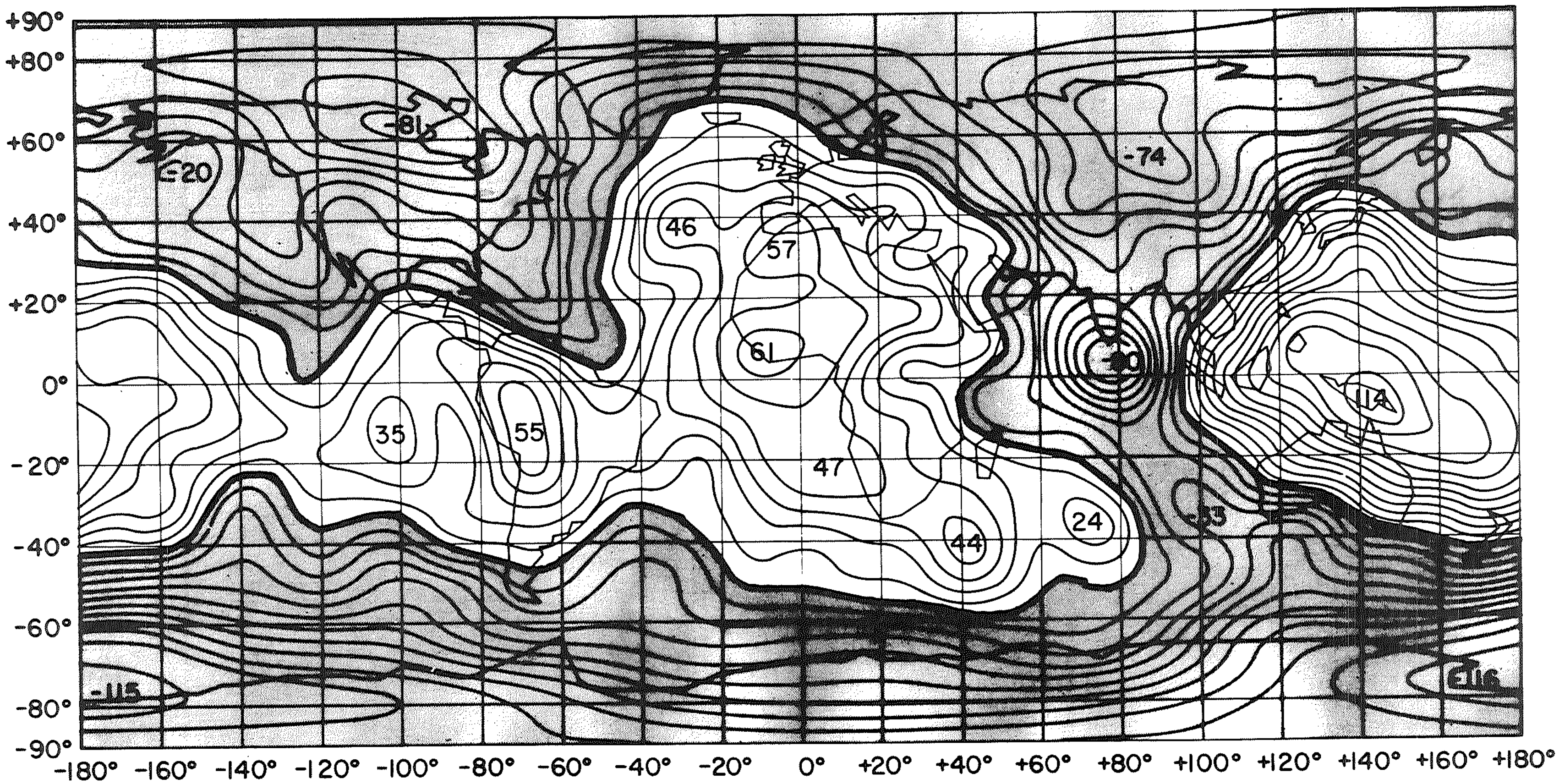

Fig. 4. Geoid heights in meters corresponding to a reference ellipsoid of flattening f = 1/299.67, from Gaposchkin and Lambeck [4].

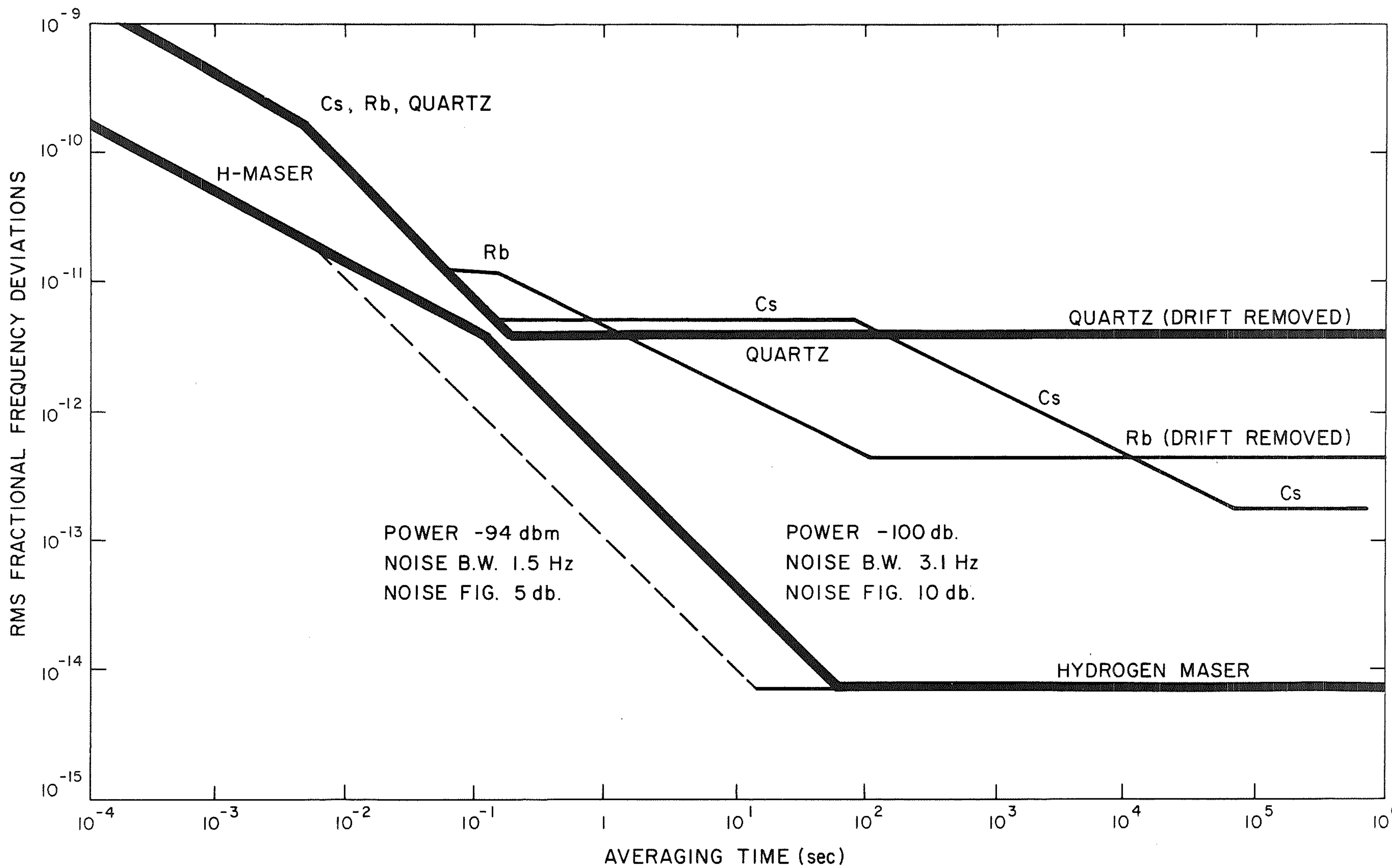

Fig. 5. Stability of frequency standards, from Levine and Vessot [14].